

# Ultimate Temperature of Steel Frames Exposed to Fire - Part 2 Stress Redistribution and Limit of Deformation of Steel Frames -

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## 1. INTRODUCTION

In this paper, the relation between the deformation and the stress redistribution of frames was considered based on the thermal analysis results. And the objective of this research was to obtain fundamental findings for the problem on fire compartments that were as important to fire safety as structures.

## 2. FRAMES FOR THERMAL ANALYSIS

Table 1 shows frames for the thermal analysis. The frames had multi stories with 3 spans. The number of the stories was 8, 12 or 15 stories, the span length was 18m (6, 6, 6 m), 26m (10, 6, 10 m), or 34m (14, 6, 14m), and  $C_b$  was 0.083 or 0.35.

Table 1 frames for analysis (unit:m)

FL (-)		8	12	15
$C_b$ (-)	0.083	6×6×6	6×6×6	6×6×6
		10×6×10	10×6×10	10×6×10
		14×6×14	14×6×14	14×6×14
	0.35	6×6×6	6×6×6	6×6×6
		10×6×10	10×6×10	10×6×10
		14×6×14	14×6×14	14×6×14

## 3. COLLAPSE MODE AND MECHANICAL EQUILIBRIUM CONDITION OF FRAMES

When fire happened in the frames with multi stories and spans, the collapse mode might change according to the structural property and the position that fire happened.

### (1) *Inner span fire*

When fire happened in the inner span, the frame fell into one of three collapse modes (a, b or c) shown in *Figure 1* in the ultimate state.

#### a) The collapse mode that the stress redistribution was fully used (*Figure 1-a*)

This collapse mode was the mode that the frame collapsed, using the stress redistribution of the overall frame fully.

Plastic hinges were formed in the beam ends of the span that adjoined the fire compartment, and the mechanical equilibrium was shown in *Figure 2*. Then, the deformation of the frame was large.

#### b) The collapse mode that the heated columns buckled (*Figure 1.b*)

When the stress redistribution of the overall frame was small, the frame lost its stability immediately after the heated column buckled, as shown in *Figure 1.b*). In this case, both the effect of the stress redistribution and the influence of the thermal stress could be disregarded because the thermal stress was small before the column buckled. Therefore, the ultimate temperature of the frame could be estimated by tangent modulus theory, as shown in *Figure 2.b*).

#### c) The collapse mode that the heated beam collapsed locally (*Figure 1.c*)

As shown in *Figure 1.c*) and *Figure 2.c*), When the stress redistribution of the frame was greatly large, the surrounding beams that redistributed the stress of columns kept themselves almost elastic. In this case, the buckling deformation of columns and the amount of subsidence did not increase like the case of *Figure 1.a*), and the temperature of heated members became higher. However, the large plastic deformation appeared only in the heated beam. Then the frame did not fall into overall collapse.

### (2) *Outer span fire*

When fire happened in the outer span, most of frames fell into one of 2 collapse modes (d or e) shown in *Figure 1* in the ultimate state.

#### d) The collapse mode that the outer span subsided (*Figure 1.d*)

This collapse mode was the mode that the upper frame of the fire compartment subsided, plastic hinges being formed in the beam ends in the adjoining span.

#### e) The collapse mode that the frame overturned (*Figure 1.e*)

This collapse mode was the mode that the frame overturned on the whole because the frame moved horizontally and rotated on the plastic hinges (a) shown in *Figure 1.e*), and then the hinges were formed in the beam ends and the column base.

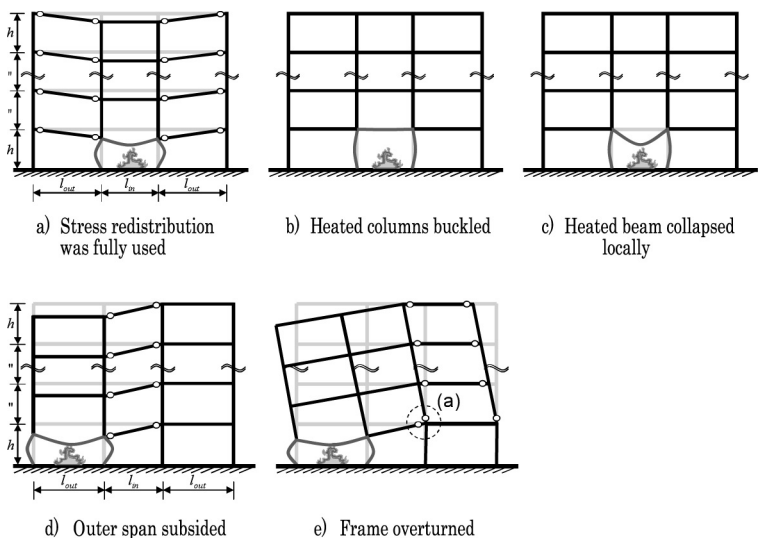


Figure 1 Collapse mechanism of frames at fire

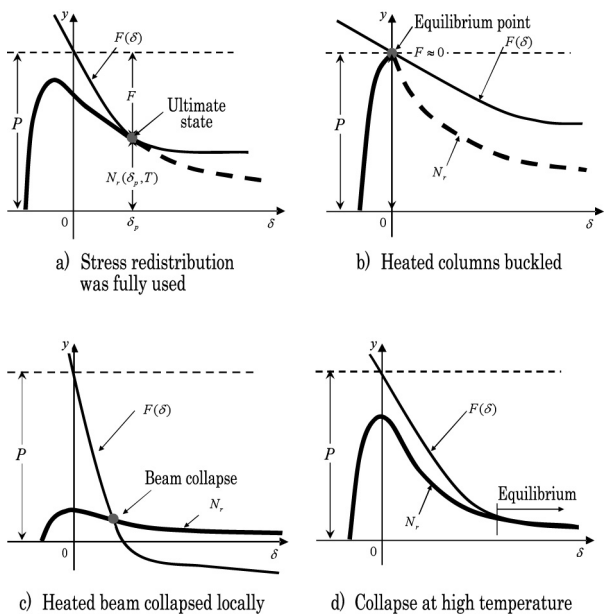


Figure 2 Equilibrium of force in the ultimate states

#### 4. ANALYSIS RESULT AND CONSIDERATION

Figure 3 to 7 showed the relation between the deformation of frames and the stress redistribution rate  $x$  in the ultimate state. In all the figures, the larger  $x$  showed the value that the fire happened in the lower floor, and the smaller showed the value that

the fire happened in the upper floor. Here,  $x$  was the value that the axial force on the column was divided by the stress redistribution.

### (1) Inner span fire

Figure 3 shows the relation between the vertical contractions on the top of the heated column  $\delta$  and  $x$ . the number of floors of the frame did not influence on  $\delta$ , but changed according to the beam length of the outer span. The longer the beam length was, the larger the contraction of column became. Figure 4 showed the relation between  $x$  and the deformation angle of the beam ( $\delta/L$ ) in the adjoining span. Then  $\delta/L$  corresponded to the contraction of the column in the ultimate state. The relation between  $x$  and the deformation of frame nearly converged on one curve by using the index of rotation angle. This showed that the deformation of the frames strongly related to the rotation angle of the beams in the adjoining span in the ultimate state.

The deformation of the frames decreased with decreasing  $x$  when  $x$  was smaller than 0.4 in Figure 4. It indicated that the frames easily felt into the collapse mode shown in Figure 1.b) and then the mechanical equilibrium of the frames was in the ultimate state shown in Figure 2.b) when  $x$  was smaller. And the deformation was almost the constant value when  $x$  was in the range from 0.4 to 0.8. It indicated that the frames felt into the collapse mode shown in Figure 1.a) and then the mechanical equilibrium of the frames was in the ultimate state shown in Figure 2.a) because the stress redistribution was fully utilized. And the deformation became smaller again when  $x$  was larger than 0.8. It indicated that the frames easily felt into the collapse mode shown in Figure 1.c) and then the mechanical equilibrium of the frames was in the ultimate state shown in Figure 2.c). Namely, the frames did not fall into overall collapse but the heated beam collapsed locally.

The upper limit of the rotation angle of the beams became almost 0.2 in the ultimate state. The rotation angle of the beams somewhat exceed 0.02 when  $x$  was nearly 0.8 in some analysis results. It indicated that the frames felt into the mechanical equilibrium shown in Figure 2.d).

### (2) Outer span fire

Figure 5 and 6 show the vertical contraction of interior columns and exterior columns, respectively. The contractions of the exterior columns were larger than the contractions of the interior columns in these Figures. It indicated that most of frames in this analysis felt into the collapse mode shown in Figure 1.e). The span length of the inner span of all frames was 6m. That was the reason why the contraction of interior column converged on one curve in all analysis results. Figure 7 showed the relation between  $x$  and the value that the contraction of the exterior columns was divided by the sum of the outer span length and the inner span length.

On the other hand, even though  $x$  showed the same tendency in outer span fire when  $x$  was smaller than about 0.4, the characteristics of the deformation of the various frames were not grasped by the rotational angle because some collapse modes appeared.

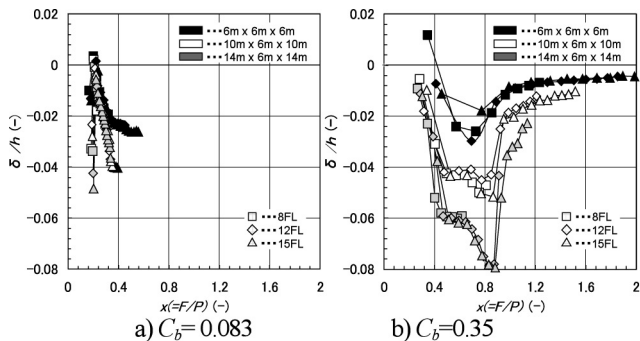


Figure 3 relation between  $x$  and the contraction of column (inner span fire)

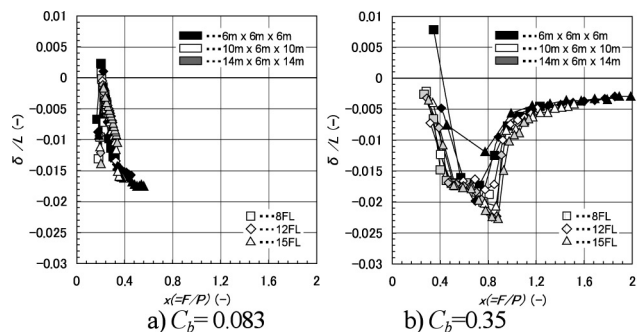


Figure 4 relation between  $x$  and the rotation angle of beam (inner span fire)

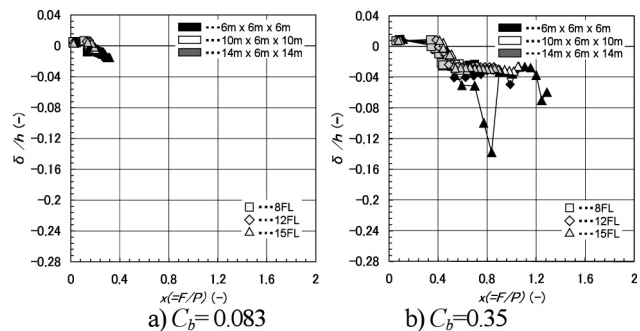


Figure 5 relation between  $x$  and the contraction of interior column (outer span fire)

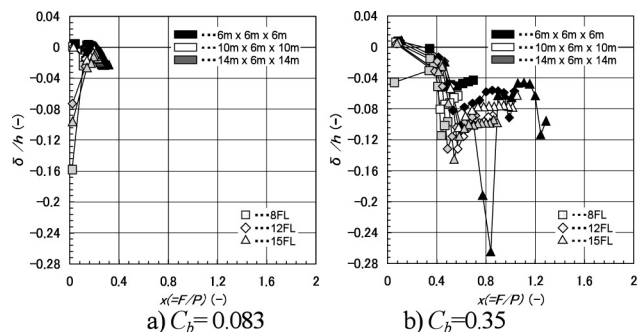


Figure 6 relation between  $x$  and the contraction of interior column (outer span fire)

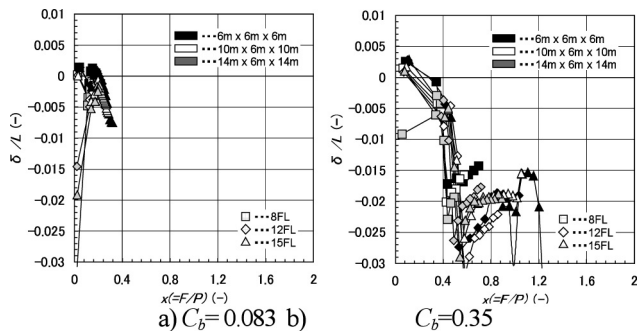


Figure 7 relation between  $x$  and the rotation angle of beam (outer span fire)

## 5. CONCLUSIONS

The deformation of frames in the ultimate state in fire related to  $x$ , and it was divided into 3 ranges according to  $x$ . The characteristics of the deformation of frames were grasped by the rotation angle of beams in the adjoining span in inner span fire. And then the upper limit of the rotation angle was nearly 0.02.